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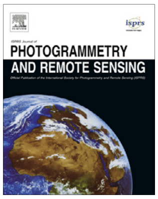

Above ground biomass estimation in an African tropical forest with lidar and hyperspectral data

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ABSTRACT

The estimation of above ground biomass in forests is critical for carbon cycle modeling and climate change mitigation programs. Small footprint lidar provides accurate biomass estimates, but its application in tropical forests has been limited, particularly in Africa. Hyperspectral data record canopy spectral information that is potentially related to forest biomass. To assess lidar ability to retrieve biomass in an African forest and the usefulness of including hyperspectral information, we modeled biomass using small footprint lidar metrics as well as airborne hyperspectral bands and derived vegetation indexes. Partial Least Square Regression (PLSR) was adopted to cope with multiple inputs and multicollinearity issues; the Variable of Importance in the Projection was calculated to evaluate importance of individual predictors for biomass. Our findings showed that the integration of hyperspectral bands ($R^2 = 0.70$) improved the model based on lidar alone ($R^2 = 0.64$), this encouraging result call for additional research to clarify the possible role of hyperspectral data in tropical regions. Replacing the hyperspectral bands with vegetation indexes resulted in a smaller improvement ($R^2 = 0.67$). Hyperspectral bands had limited predictive power ($R^2 = 0.36$) when used alone. This analysis proves the efficiency of using PLSR with small-footprint lidar and high resolution hyperspectral data in tropical forests for biomass estimation. Results also suggest that high quality ground truth data is crucial for lidar-based AGB estimates in tropical African forests, especially if airborne lidar is used as an intermediate step of upscaling field-measured AGB to a larger area.

1. Introduction

Remote sensing of forest aboveground biomass (AGB) has received increasing attention during the last decade due to its relevance to global carbon cycle modeling and to international programs aimed at reducing greenhouse gas emissions in tropical areas, such as the United Nations Reducing Emissions from Deforestation and Forest Degradation (REDD+). In particular, biomass mapping in tropical biomes is particularly important given the critical role of tropical forests in the global carbon cycle (Gibbs et al., 2007). Recent findings show that tropical forests store 21% more carbon than previously expected (Baccini et al., 2012). While the biomass of most temperate and boreal zones has been systematically inventoried at least once (Houghton et al., 2009), tropical regions suffer from operational limitations and consequent lack of data, which is especially marked in Africa (Baccini et al., 2008).

Airborne small-footprint Light Detection and Ranging (lidar) is considered the most accurate remote sensing technology for mapping biomass (Zolkos et al., 2013) and could be useful in filling this information gap. Discrete return (DRL) or full waveform (FWL) small-footprint lidar systems are now widespread and operated around the globe, enabling the collection of up to four returning energy pulses (as DRL) or all the returning energy (as FWL) from the forest vertical profile. The laser pulse returns are usually used

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to derive forest height metrics, which can then be related to field-observed AGB, with the latter obtained by means of field measures and allometric relationships. Due to the high operational costs, lidar-derived AGB estimates usually can only be obtained over limited areas. These local-scale or sub-national accurate estimates are crucial for REDD+ measuring, reporting, and verification (MRV), and for country level natural resources management and inventories (Næsset, 2007; Peterson et al., 2007). Local AGB maps are also the basis for the extension of estimates to larger areas using remote sensing approaches (Asner et al., 2010; De Sy et al., 2012). However, to date there has been little research into mapping of biomass in tropical forests using airborne small-footprint lidar. Zolkos et al. (2013) conducted a comprehensive review and identified eight studies carried out with this system in tropical forests, with none in continental Africa.

The uncertainties associated with the current knowledge of the African ecosystems' carbon balance are rather high. A review of the most recent estimates of the net long-term carbon balance of African ecosystems, based upon observations, indicated a sink of the order of 0.3 Pg Cyr^{-1} with a very high uncertainty and a variable source; up to now many questions remain open, and it is unclear whether Africa is a net carbon source or a sink to the atmosphere (Ciais et al., 2011). Because of highly variable CO_2 fluxes and insufficiently studied ecosystems and ecosystem–human–climate interactions, there is a need for continued and enhanced observations of carbon stocks, fluxes and atmospheric concentrations to enable more precise assessments of Africa's carbon cycle (Justice et al., 2001), and its sensitivity to natural and anthropogenic pressures and future climate. Of primary importance is the need for continent-wide carbon cycle observations that support both bottom-up and top-down methods of estimating carbon sources and sinks (Lewis et al., 2009). An African integrated carbon-observing system is needed, encompassing both: (i) regional inventories and monitoring of soil and vegetation carbon stocks by forest and agricultural research stations; (ii) remote sensing-based estimates of forest biomass C stock distribution, at different scales and using active and/or passive sensors combined with field observations. In view of the above considerations regarding the contributions of African forests in the global carbon cycle, it is clear how valuable it is to test biomass mapping by means of various sensors over different African forests.

Hyperspectral sensors, recording the reflectance of a large number of fine resolution spectral bands from visible to near infrared (NIR) or shortwave infrared (SWIR) range, are another frontier technology in remote sensing. Hyperspectral data can capture information regarding the biochemical composition of the upper canopy layer and have been used for forest type or species classification, estimation of biophysical and biochemical properties and health status (Asner and Martin, 2008; Koch, 2010; Goodenough et al., 2006). The ecosystem information recorded by hyperspectral data may relate to plant functional types – such as whether a species is light demanding – which could in turn affect wood density and thus biomass content (Baker et al., 2004; Chave et al., 2009). Hyperspectral data have been used to estimate grassland biomass directly (Cho et al., 2007; Psomas et al., 2011) and leaf canopy biomass (le Maire et al., 2008), while leaf area density, retrieved from fusion of hyperspectral and radar data, has been used in the estimation of forest AGB (Treuhaft et al., 2003). The few studies that have attempted to improve biomass estimates in boreal, temperate and tropical forests by combining hyperspectral imagery with lidar data have reported only modest or no improvement in model fit compared to the results from using lidar only (Anderson et al., 2008; Clark et al., 2011; Latifi et al., 2012; Swatantran et al., 2011). Despite these research efforts, the number of published studies on integrating lidar and hyperspectral data for biomass estimation is rather small. Further research is needed along this line, especially considering the opportunities from forthcoming hyperspectral missions, such as the Environmental Mapping and Analysis Program (EnMap), the PRecursore IperSpettrale of the application mission (PRISMA), the Medium Resolution Imaging Spectrometer (MERIS) and the Hyperspectral Infrared Imager (HyspIRI).

The main objectives of the present study are the following: (i) to test for the first time small footprint lidar-based AGB retrieval in a West African tropical moist forest, (ii) to examine whether the use of very high spatial resolution hyperspectral data in addition to lidar can improve the biomass estimates.

2. Materials and methods

2.1. Study area and ground truth data

The study area is within the Gola Rainforest National Park (GRNP) in Sierra Leone, at the westernmost end of the humid Upper Guinean Forest Belt, in West Africa (Fig. 1).

The forests of this region are largely lowland moist evergreen forest with some areas towards lowland dry evergreen and semi-deciduous forest types (Cole, 1993). Within GRNP Klop et al. (2008) identified moist evergreen, moist semi-deciduous, freshwater inland swamp forest, forest regrowth and secondary/disturbed forest. The GRNP area has been protected through conservation programs since 1989 but commercial logging, most intensively in the southern block, was carried out in 1963–1965 and 1975–1989. Recent land cover mapping (Vaglio Laurin et al., 2013) highlighted the importance of conserving this forest from anthropogenic pressure in the surrounding areas. The climate is moist tropical, with annual rainfall around 2500–3000 mm, a dry season from November to April coincident with leaf-off condition of some semi-deciduous tree species, and an altitude of 70–410 m.

Field data collection carried out in 2006–2007 in the GRNP established over 600 plots of 0.125 ha each across the whole park area, recording species information as well as structural and environmental forest parameters. In the plots, all trees with Diameter at Breast Height (DBH) > 30 cm were recorded, while trees with DBH included in the 10–30 cm range were measured in a 1/10 smaller subplot. Height measures were derived with a local DBH-height relationship and the AGB was obtained applying the Chave et al. (2005) general equation for moist tropical forest including DBH, height and wood density values. The data collection protocol and the allometric procedure are fully documented in Lindsell and Klop (2013). We selected all the plots surveyed by both lidar and hyperspectral sensors excluding some plots located less than 1 km from the park boundary where land cover changes were most likely to have occurred in the period between field and aerial data collection. We also excluded plots affected by cloud shadow in the hyperspectral data. We retained 70 ground truth plots, with an AGB range 0–586.9 Mg ha^{-1} (mean = 172.2 and standard deviation = 111.8 Mg ha^{-1}). These plots contained 136 species with DBH > 30 cm, and 86 occurring in the upper canopy layer.

2.2. Remote sensing data

The central and parts of the southern blocks of GRPN were surveyed by an airborne campaign in March 2012 over pre-defined flight lines covering part of the field, using a Pilatus PC-6 Porter aircraft equipped with lidar and hyperspectral sensors and a digital camera for aerial photographs.

The lidar sensor ALTM GEMINI (Optech Ltd.), characterized by a 1064 nm laser wavelength and able to record up to 4 range measurements, was operated between 650 and 850 m above ground level (AGL). The minimum laser density was set to 11 points/m^2. The